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ABSTRACT

We have measured the contrast of solar faculae near the limb on direct digital video images made with the 65 cm vacuum reflector at the Big Bear Solar Observatory. We used six broad band filters with different wavelengths from red to violet. The range of heliocentric angle covered in our measurements is $0.05 < \mu = cos\theta < 0.4 (\theta = 87° - 66°)$. About 300 images were measured from observations made during the summers of 1983 and 1985. Over 20000 facular points were measured.

By averaging the contrasts of faculae and plotting them vs. heliocentric angle, we found that contrast increases monotonically towards the limb for the shorter wavelengths; for longer wavelengths, contrast has a tendency to peak around μ=0.15, and then decrease towards the extreme limb. The contrast increases as wavelength decreases.

1. Introduction

Faculae are regions of enhanced magnetic field observed in the continuum. It is well known that the contrast of the facula to the photosphere increases toward the limb (Muller, 1975). But the exact behavior of the contrast function near the extreme limb has been a matter of some dispute. The question was especially active in discussions of measurements of the solar oblateness (Chapman and Ingersoll, 1970), but the center-limb variation of facular brightness is important evidence on the physical nature of faculae. Why the presence of enhanced magnetic field produces these increases is a mystery.

The variation in measurements made by various authors (Chapman and Klabunde, 1982; Muller, 1975; Libbrecht and Kuhn, 1984, 1985) is summarized in figure 1 (copied from Libbrecht and Kuhn) where we have included our results. Almost all the previous measurements are indirect, i. e. all the faculae within a

range were measured, and the area estimated. The wavelength range of the previous data is also limited. The data of Chapman and Klabunde are based on integrated observations of bands of constant μ while that of Muller is based on photographic observations in a single wavelength on four days. There have been no previous digital photometric measurements of individual facular points; this would appear to be the most direct and simple way of measuring the contrast when resolution is adequate. This method also permits us to approach much closer to the limb than previous data. Our data go to $\theta = 85°$, 5 arc sec from the limb.

Two kinds of theoretical models which attempt to explain the excess continuum emission of the faculae over the quiet photosphere: (1) The 'Hot Wall' model (Spruit, 1976). (2) The 'Hot Cloud' model (Chapman, 1970; Ingersoll and Chapman, 1975). The 'Hot Wall' model predicts that the contrast of facula peaks at a heliocentric angle of $\cos\theta = 0.2$ then decreases rapidly. The 'Hot Cloud' model predicts a rapid increase of the facular contrast when $\mu < 0.2$. The measurement of the center-to-limb variation in facular contrast gives an important test of those models.

2. Instrument and Data Collection

For the present work we used a RCA camera with Newvicon vidicon tube on the 65 cm reflector at Big Bear. Frames were digitized with eight–bit accuracy on the Quantex or Eyecom video image processors. Usually four successive frames were averaged to reduce video noise. The total exposure is thus 1/8 second. A photograph of one of the plage regions is given in Fig. 3. The resolution in the BBSO in the summer is usually about 1 arcsec. A rotating filter wheel made possible rapid change of the wavelength observed. The video image processors make possible the direct measurement of intensities within small polygons on the images.

Measurements of step wedges showed our system to be linear within a few per cent. For the small contrast of facula to photosphere this is adequate. We placed a small piece of neutral filter with a transmittance around 50-80 percent in front of the TV camera for gain calibration.

We checked scattered light by measuring the scattered light off the limb. For most images it was below the Newvicon threshhold, or less than a few percent . As a check, we obtained limb darkening curves for 3862Åand 5250Åwhich are presented in figure 2. They are compared with the limb darkening curves from

the parameters in Allen's Astrophysical Quantities. Our observed curves coincide within 5 percent with Allen's curve except at $\mu = 0$. That means scattered light is not significant and we made no scattered light correction. A filter wheel was used to shift rapidly from one to another of six wavelengths; neutral filters were used to keep the images within the range of the vidicon. The accuracy and repeatibility of a single measurement with this system is about one per cent, but the accuracy for a facular point is somewhat less because of calibration and position registration errors.

The video image in figure 3 was obtained on May 4, 1983 at 3862Åand 7140Å. The scale size of the faculae is marked. Because the scale of the image is very large, the limb of the sun can be taken as a straight line. We see that the plage is an array of small points or strings of points, many of which are smaller than one arc sec.

3. *Data Analysis*

Our measurements were obtained in the summer of 1983 and 1985 on about 35 active regions on 25 days. The broad band filters used were 3470Å, 3862Å, 4642Å, 5250Å, 5700Å and 7150Å for 1983; and 3862Å, 4642Å, 5250Å, 5700Å, for 1985.

We used two different analysis methods to reduce our data.

(a) For the 1983 data, we randomly selected many facular points, averaged the peak contrast of every facula within bins of $\delta\mu$=0.05, then plotted the contrast vs. μ. We used about 150 images, 10 to 20 points in each.

(b) For 1985 data, in order to get rid of any bias in selecting faculae points, we used a more automatic technique. We plotted a profile parallel to the limb of the sun and found the average intensity and noise (i.e. standard deviation) along this line. Any point on this line with contrast larger than 3 times the noise level, was chosen as a facular point. We repeated this procedure for about 130 images in 4 wavelengths. On the average, about 2000 facular points are identified in each image. Finally, we averaged the contrast within bins of $\delta\mu$=0.05, and then plotted contrast vs. μ. There is one problem in this method, ie. the ratio noise/average intensity increases as μ decreases, which removes the low contrast faculae from our sample.

This tends to increase the contrast measured close to the limb. In order to solve this problem, we did the following and we call this procedure *normalization*:

Suppose the facular contrast has the Gaussian distribution:

$$n(I) = ae^{-bI^2} \tag{1}$$

a,b are constants, and I is the contrast.

The total observed number of facular points within the bin i is:

$$N_i = a_i \int_{3S_i}^{\infty} e^{-b_i I^2} dI \tag{2}$$

S_i is the average noise/photosphere signal in given μ bin. The observed average contrast within the bin is :

$$\overline{I}_i = \frac{\int_{3S_i}^{\infty} I e^{-b_i I^2} dI}{\int_{3S_i}^{\infty} e^{-b_i I^2} dI} \tag{3}$$

Combining equation (2) and (3), b_i can be found. Finally, we set noise/intensity$=S_0$ for all the bins, so that the normalized average contrast is:

$$(\overline{I}_i)_0 = \frac{\int_{3S_0}^{\infty} I e^{-b_i I^2} dI}{\int_{3S_0}^{\infty} e^{-b_i I^2} dI} \tag{4}$$

The effect of the *normalization* will be discussed in the next section.

4. Results and Discussion

Our results are given in the figures. Figure 1 shows those for $5250\overset{\circ}{A}$ compared to those of other authors. Our results, shown by circles, show neither the sharp dropoff deduced by Libbrecht and Kuhn (1984) nor the sharp increase found by Chapman and Klabunde (1982). Instead the slowly rising contrast reaches a maximum near $\mu = 0.15$.

The contrast vs. $\cos\theta$ is plotted in Figure 4 for 1983's observations. The facular contrast increases monotonically towards the limb at shorter wavelengths. At longer wavelength, the contrast increases towards a maximum around $\cos\theta=0.15$ to 0.10, then decreases limbwards.

In Figure 5, we include the μ and contrast relation for 3 different situations. (1) Before the normalization; (2) After the normalization, set $S_0 = 0.0$; (3) After the normalization, set S_0 = average noise/intensity over the all the bins.

The normalization increased the number of weaker facular points in our sample as $\cos\theta$ approaches the limb. We can see that after the normalization, the qualitative behavior of the contrast is independent of the choice of S_0, i.e. the facular contrast increases monotonically towards the limb at shorter wavelengths. At longer wavelength, the contrast increases towards a maximun around $\cos\theta=0.15$ to 0.10, then decreases limbwards. It is same as the conclusion we got from 1983's data. However, if the smaller S_0, is chosen, the facular contrast is reduced systematically. The normalization has a significant effect only at the two bluest wavelengths.

The contrast of the facula as a function of wavelength is plotted in figure 6. From figure 4, 5 and 6 , it is obvious that the contrast increases as wavelength decreases at the same $\cos\theta$.

The method we used supposes a relatively constant distribution of facular brightness, and uses the average brightness as a measure of the changes in individual faculae as they approach or leave the limb. Time variation should average out. One might think a better way is to measure the change in individual facular points. We tried this method and found it wanting. Near the solar limb, the μ of a particular facula changes form 0.3 to 0.1 in less than 24 hours. To find out the behavior of the contrast of the individual faculae near the extreme limb, several observations for the same active region should be made during one observing day. Unfortunately, in this way, the curve of the contrast turns out to be the diurnal seeing curve, the contrast peaking at noon when the seeing is best. Further, individual facular points are hard to identify from one observation to the next. The results are therefore not significant and not included here.

The statistical analysis appears the most practical way to find how the contrast varies with the heliocentric angle. The average brightness of all the points appears to be a stable and repeatable measurement.

5. *Error Analysis*

There are several sources of error in this data, as follows:

(a) The limb fit: The points which have maximum pixel value gradient in a image were chosen as the locus of the limb. The error arising from this limb fit could be about 3-5 pixels. So when $\mu > 0.1$, the error for μ is less then 10 percent .

(b) Calibration: The system is slightly nonlinear (D. Chou and Z. Shi, personal communication). If the contrast is less that 30 percent, the error from nonlinearity is less then 5 percent. So the nonlinearity is more important for large sunspots then for faculae.

(c) Selection effect for 1983 observation. i.e. the tendency to miss weak faculae near the extreme limb, increases the average contrast of those points measured near the extreme limb.

(d) Because many of the points are unresolved, the true contrast of the facular points must be greater than that measured. But since brightness is averaged over pixels, the total brightness of the facular point is unaffected.

The difficulty involved in obtaining accurate measures of facular intensity is obvious. The faculae may change in intensity from day to day. The seeing may change. Because of the variations in faculae, we felt that a large sample (in this case, about 20000 facular points) would give a reasonable representation of the run of facular brightness. The relatively low scatter of the results suggests that it does.

6. *Discussion*

Our statistical measurements of a large number of faculae show that they behave as one would expect from cursory examination of a high resolution photo. For shorter wavelengths, the contrast facula increases monotonically limbwards; for longer wavelengths the facular contrast shows less change with position and at 7150Å peaks around $\mu=0.1$ to 0.15, and then decreases towards the limb slightly. We find no great deviation near the extreme limb; the facular contrast neither dives nor skyrockets, as has been suggested by the various indirect measurements.

The contrast increases as wavelength decreases at the same $\cos\theta$.

Our results do not show the high contrast obtained by Chapman and Klabunde, since we observed all the faculae directly, there is no way in which objects of such high contrast could have been missed.

Another important result lies in the fact that we make an integral brightness measurement. It has been suggested Stenflo (1976) and others that the magnetic elements involved in faculae are extremely small, rather strong (1000 gauss or more) and unresolved by magnetograms. Thus a magnetograph making an average measurement over a few arc seconds would give a field of 10 gauss when the flux element really is 1000 gauss in an 0.1 arc second area. Our measurement, however, is an integral measurement; if the facular element has a filling factor 100 (0.1 arc sec), then it must be 20 times brighter than the photosphere to produce the 20 percent enhancement which is the peak observed here. Even in the red the brightness increase would have to be a factor 10. Since this is the Rayleigh–Jeans region a temperature of 60,000° would be required, which would produce enormous ultraviolet enhancements. It might be argued that magnetic clumping only exists in invisible sunspots, and the faculae occur in the surrounding non-magnetic region. This escape contradicts the almost perfect correspondence of faculae with magnetic fields and does not correspond to the invisible sunspot models of Spruit (1976) where the facula is due to the hot wall of the Wilson depression and must be the same scale as the invisible spot.

Why is the contrast greater in the blue? This must be the result of enhanced line absorption; spectroheliograms in blue windows near the CN band head by Sheeley (unpublished) show no faculae at disk center, while those in the band head are well-marked. Similarly, pictures in the UV (Foing and Bonnet, 1984) show strong facular contrast at 1600Å.

The peak in contrast at $\mu = 0.1$ in the near IR may be due to surface roughness. Roughness of the order 20 km in the granule tops would provide such a flattening if the facula is slightly depressed.

Acknowlegements

Figure 1. The facula contrast vs. $cos\theta$. All the measurements are at 5250Å. Bold solid line is deduced by Libbrecht and Kuhn; lighter solid line is Spruit's theoretical curve assuming a 2000 Gauss magnetic field; the dotted curve is the measurement of Muller; the dot-dashed curve gives the measurement of Hirayama; the dashed curve represents the measurement of Chapman and Klabunde. the circles show our 1985's measurements normalized to contrast=0.2 when $cos\theta = 0.2$.

Figure 2. Limb darkening curves for 3862Åand 5250Å. Solid lines represent theoretical limb darkening curve by using the parameters from Allen's 'Astrophysical Quantities.' The circles show our measurement on May 4, 1983. Because the solar disk center is not covered in our images, we assume the intensity at $cos\theta$=0.25 equals to the theoretical value ($cos\theta$=0.25 located in the middle of the images) and intensity at other $cos\theta$ is scaled by it.

Figure 3. Photograph of the video image at the solar west limb at 20:15 UT in May 4, 1983. Observed at 3862Åand 7140Åwith the 65cm vacuum telescope. The obscured at lower left is a neutral density filter.

Figure 4a-4f. The averaged facula contrast vs. $cos\theta$ for 1983.

Figure 5a-5d. The averaged facula contrast vs. $cos\theta$ for 1985. Circles are from the data before normalization; triangles represent the data after normalization by setting $S_0 = 0$; stars represent the data after normalization by setting S_0=average noise/intensity, 0.068 for 3862Å, 0.029 for 4642Å, 0.025 for 5250Å, 0.017 for 5700Å.

Figure 6a-6c. The averaged contrasts of faculae as a function of wavelength. It was averaged for 1983's data.

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Figure 1

Figure 2a

3862A

Relative Intensity — COSθ

Figure 2b

5250A

Relative Intensity — COSθ
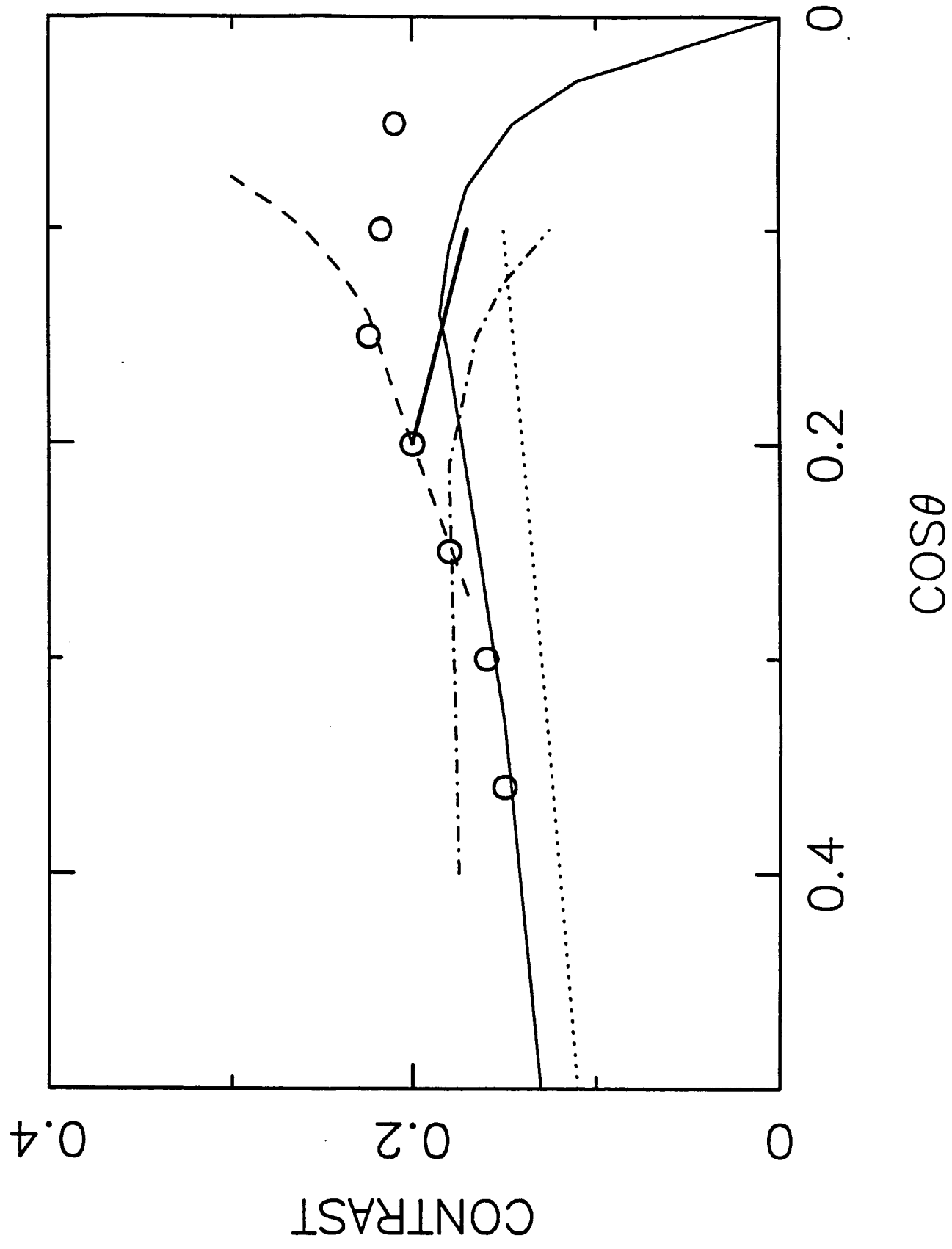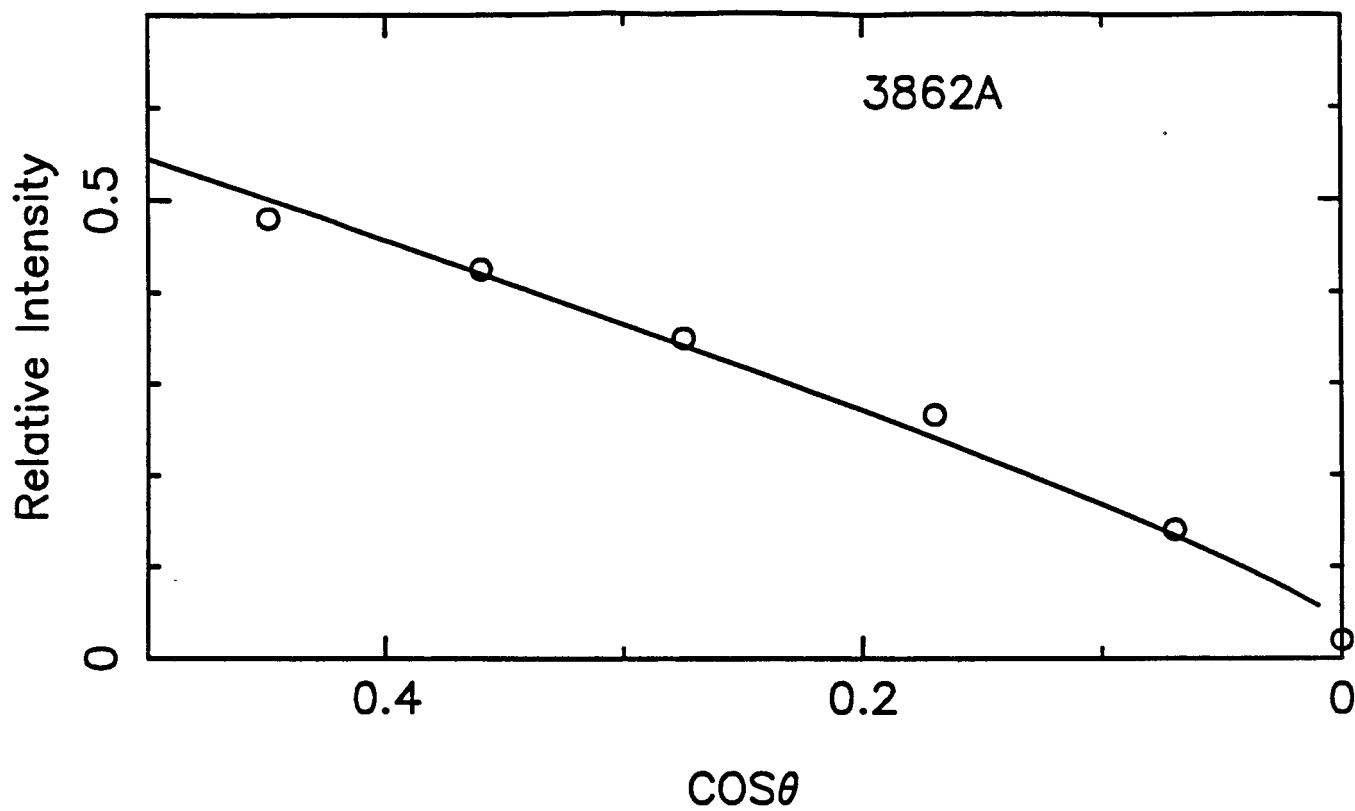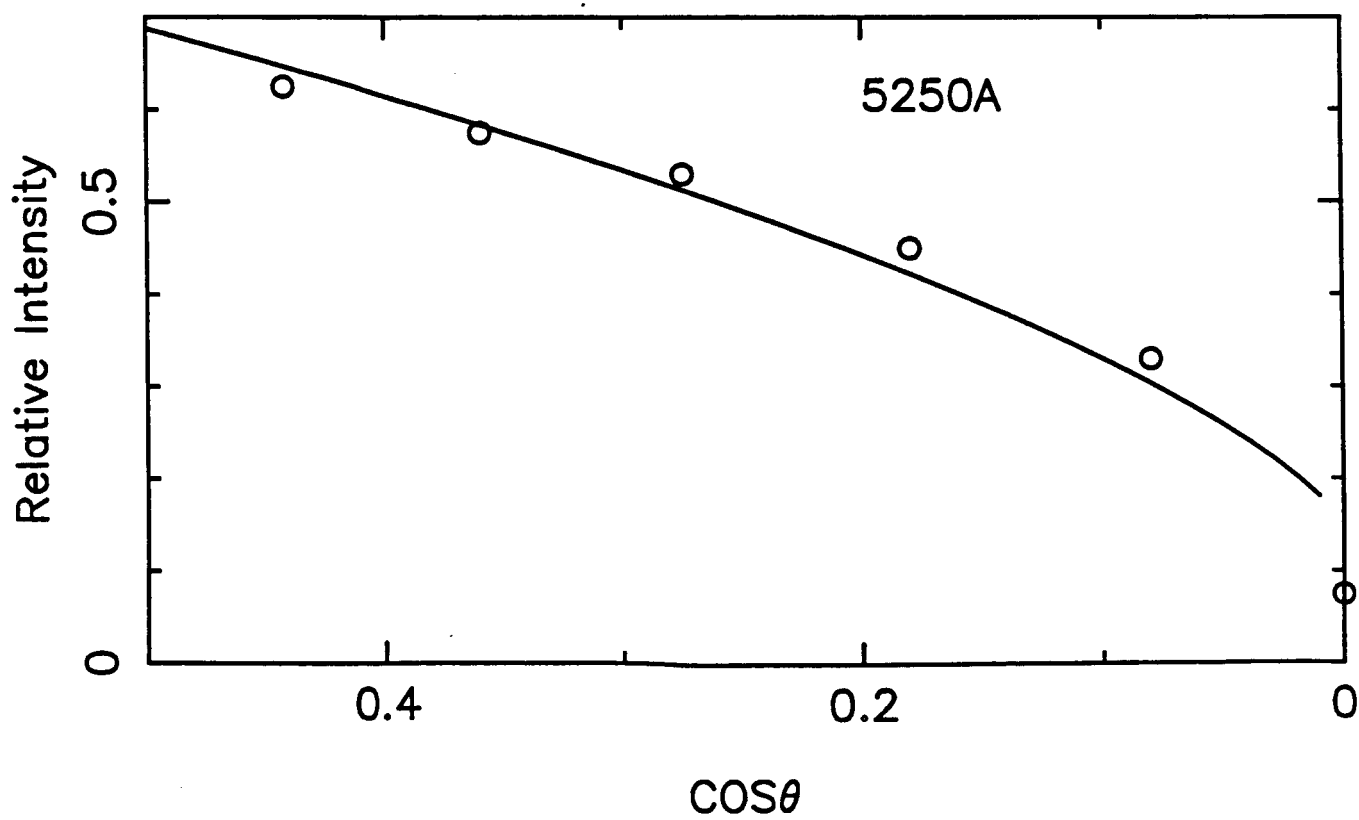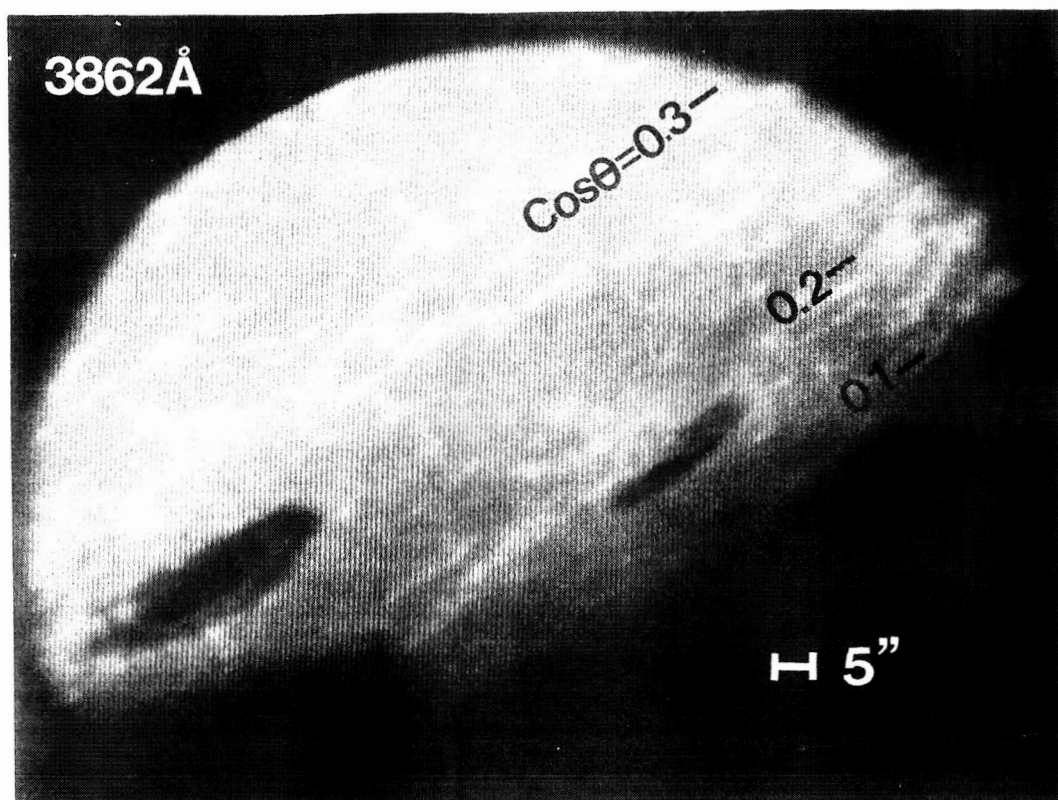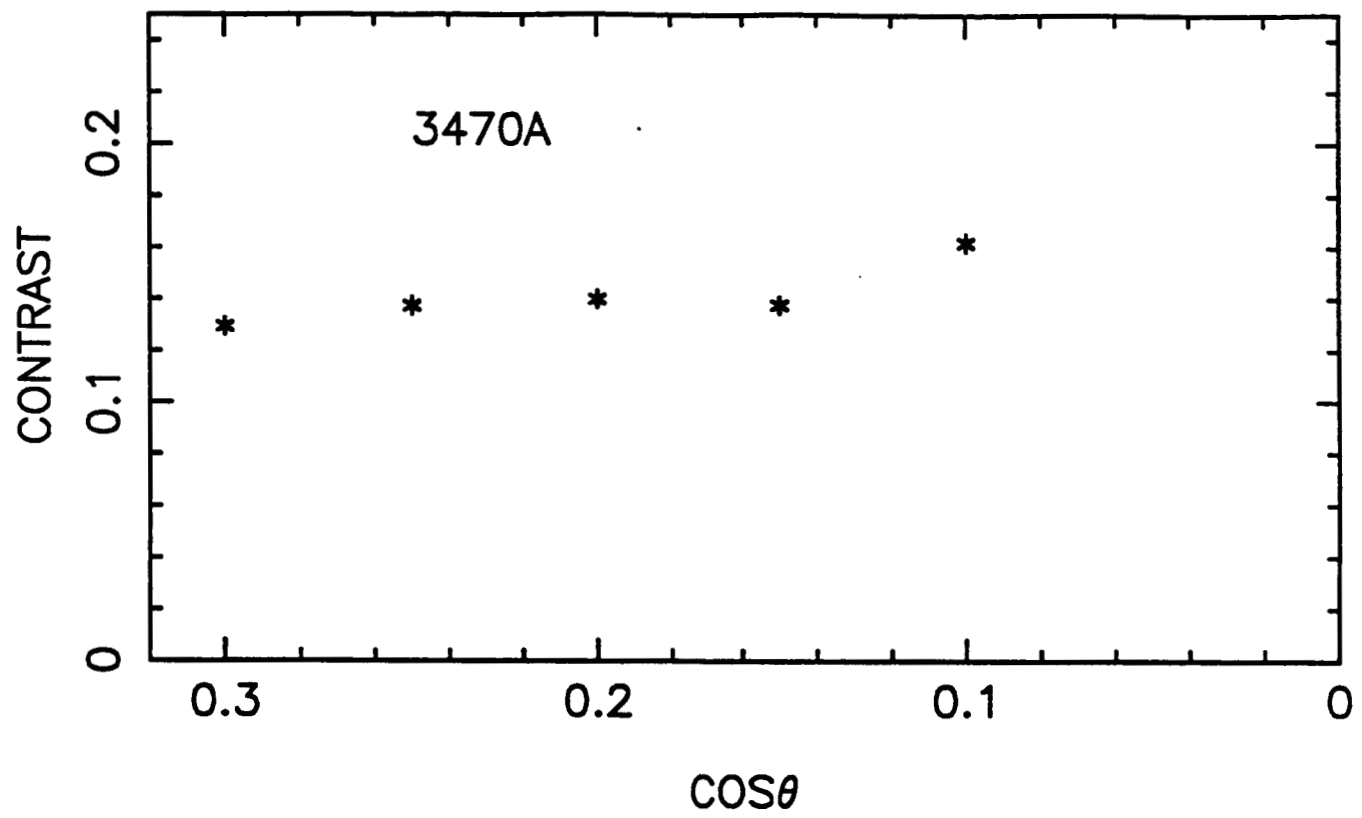
Figure 3

Figure 4a

Figure 4b
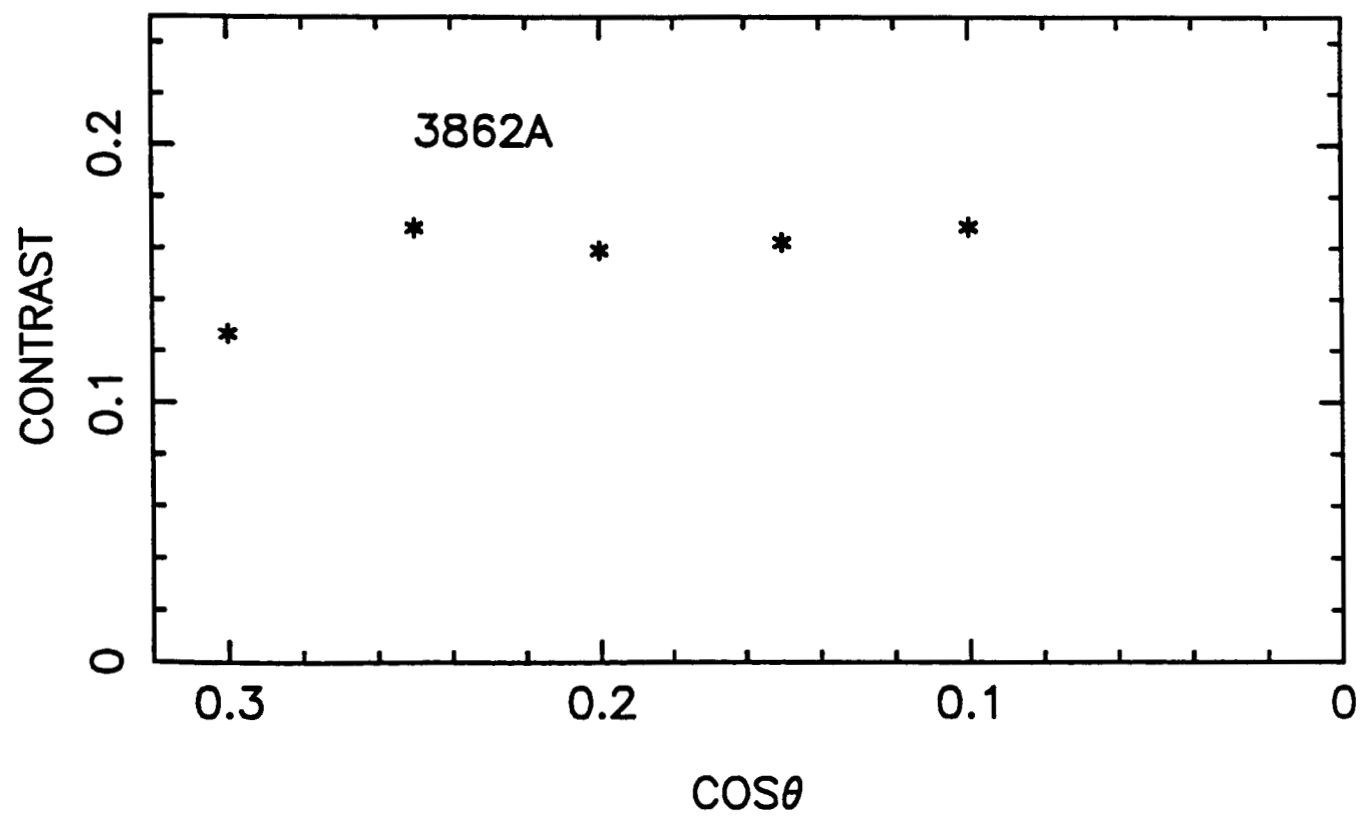
Figure 4c
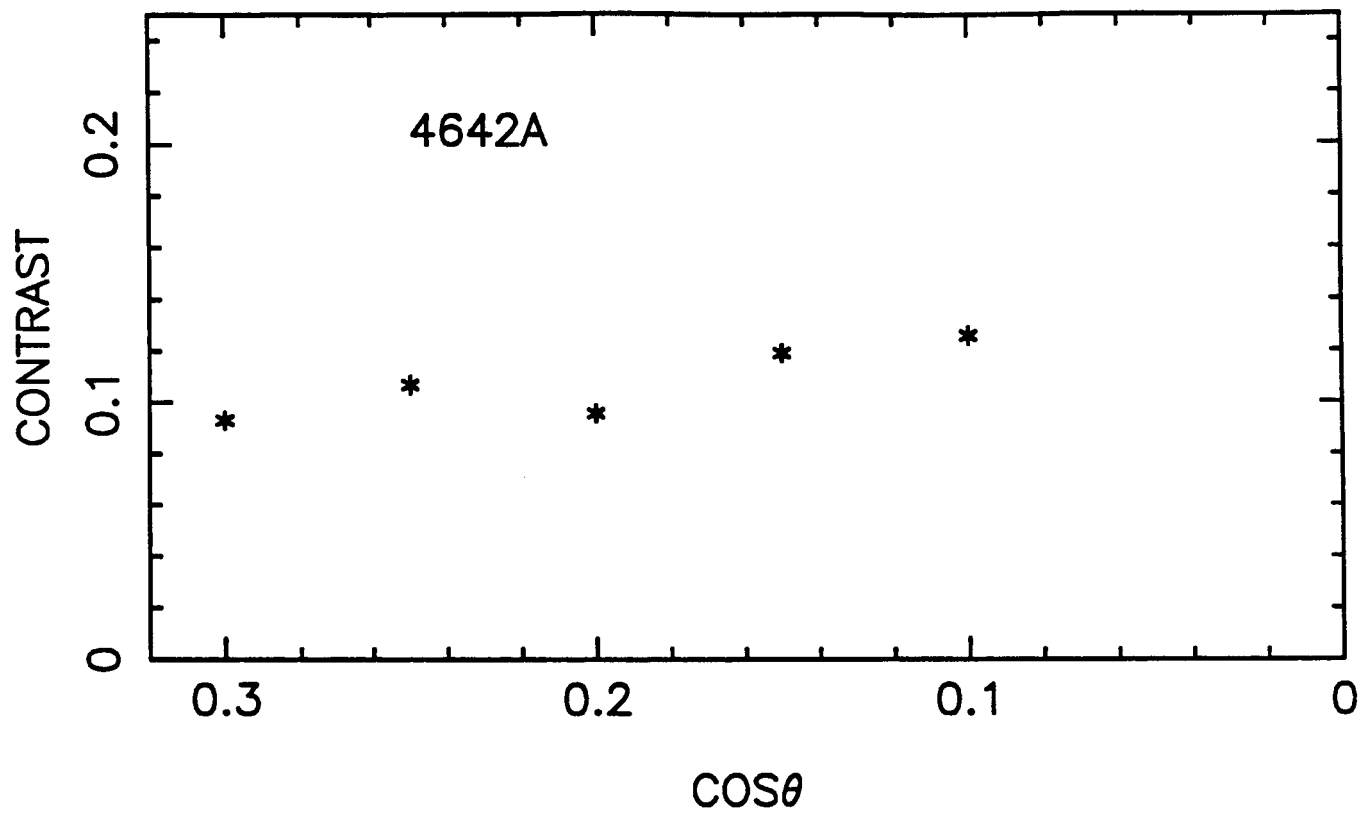
Figure 4d
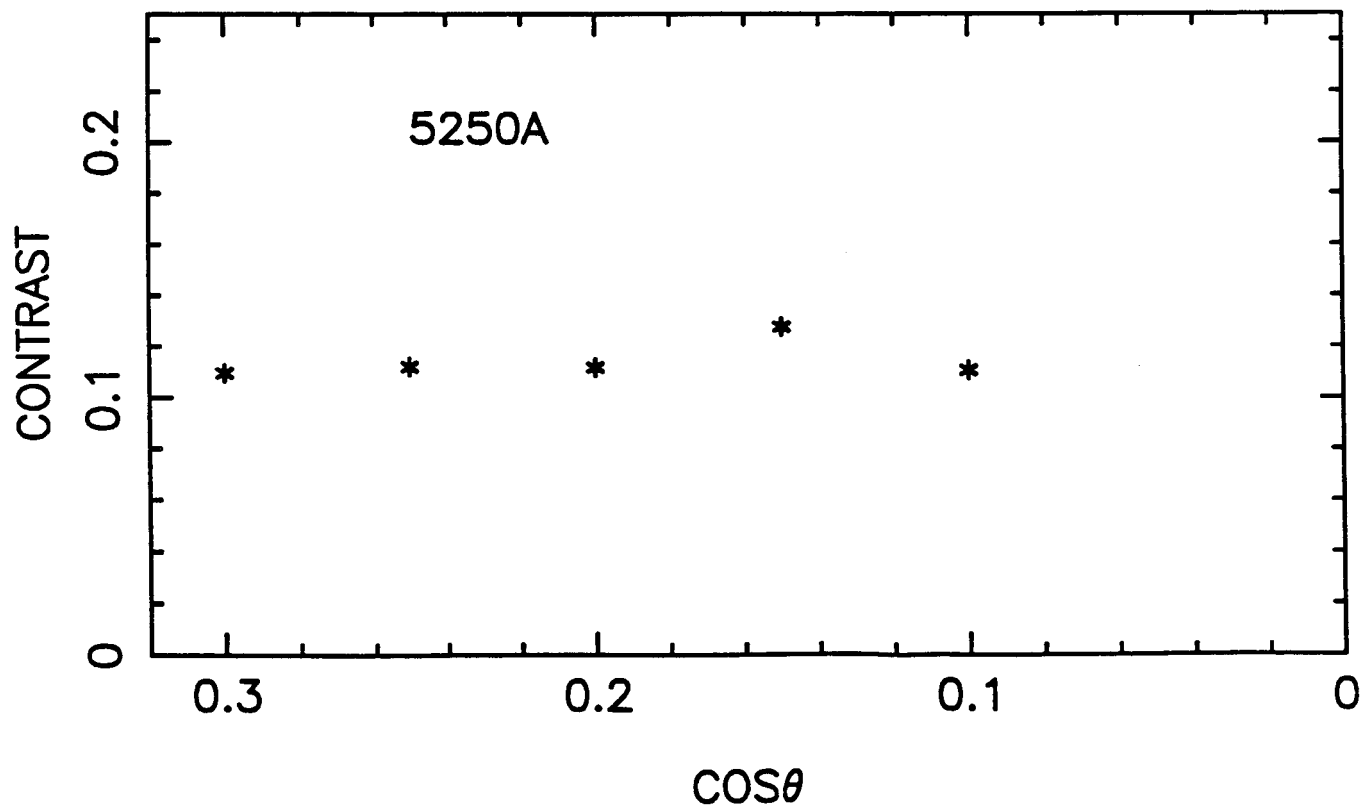
Figure 4e

Figure 4f

Figure 5a

3862A

CONTRAST

COSθ

0.4 — 0.3 — 0.2 — 0.1 — 0

Figure 5b

4642A

CONTRAST

COSθ

0.4 — 0.3 — 0.2 — 0.1 — 0

Figure 5c

5250A

CONTRAST

0.4

0.2

0

0.3   0.2   0.1   0

COSθ

Figure 5d

5700A

CONTRAST

0.4

0.2

0

0.3   0.2   0.1   0

COSθ

Figure 6a

COSθ=0.10

CONTRAST

WAVELENGTH(A)

Figure 6b

COSθ=0.20

CONTRAST

WAVELENGTH(A)

Figure 6c